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Formation of Danube delta beach ridge plains and signatures in morphology

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ABSTRACT

Danube delta, as most of the large deltas, favours complex interactions between river sediment supply and marine dispersing forces which create complex configurations with concurrent morphologies (i.e. river-versus wave-influenced) or processes (accretion versus erosion) and even distinct landscapes for the same accretionary features: strandplains with low monotonous beach ridges or covered by transgressive dunefields. Beach ridge plains (BRPs) are a common feature of the wave-influenced deltaic lobes, that are created by juxtaposition of succesive berms on the prograding sandy coasts with different shapes and sizes depending on the accretionary mechanisms and the accomodation space.

This study reports the formation and dynamics of Danube delta BRPs based on numerical age determination (OSL and AMS) of the paleoshorelines, topographic and geophysical (GPR) surveys and stratigraphic records by cores. A chronological framework is established for all deltaic BRPs which points to the importance of formation timespan and growth rate (as a consequence of sediment supply) on the resultant morphology varying inter-site from small BRP (formation time < 300 years) to large quasi-equilateral triangle-shaped BRP (1400–3000 years) and intra-site from low ridgesets with subparallel beach ridges (progradation rates of 3.5–12 m/yr) to high ridgesets where the original configuration was replaced by massive parabolic dunes or transgressive dunefields (progradation rates ≤ 3.5 m/yr). A six-type morphogenetic classification of BRPs is discussed in respect with the various spatial patterns of progradation – from the large strandplains developed on the updrift side of asymmetric lobes to the small ones accommodating the prograding sectors of the river mouths spits – and with the progradation types encountered: i) beach face accretion during fair-weather, ii) nearshore bar welding, and iii) berm crest building during storms. Although the last is building ca. 1.5% from deltaic BRPs, this is the only case when the visible beach ridges are made by wave processes. For the other two, the aspect of “beach ridges” is the result of aeolian processes that create either unitary foredune or thin eolian sheets (incipient foredune) tens of centimeters higher than adjacent berms.

1. Introduction

Beach ridge plains (BRP) are acknowledged as ubiquitous, predominantly accumulative, wave dominated progradational features which sequence stratigraphy holds a detailed record of coastal evolution (although gaps in sedimentation or hiatuses in stratigraphy are acknowledged) in terms of successive paleoshoreline position, local sea level, climate and sediment budget history. Extensive works have been worldwide undertaken on beach ridge plains developed in various environmental settings and large amount of information has been gleaned during the last century.

Continuous improvements in investigation techniques, not only the progress in OSL dating methods (Duller, 2004) – brought about by the latest developments in equivalent dose estimation (De) with the development of the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000, 2003), in the measurement facilities (Bøtter-Jensen and Murray, 1999) – but also the advances of geospatial techniques in mapping coastal geomorphology (Allen

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et al., 2012) and geophysical surveys (Neal, 2004; Bristow and Pucillo, 2006; Buynevich and Donnelly, 2006; Barboza et al., 2009), as well as novel approaches such as geoarchaeological interdisciplinary studies (Bruckner et al., 2006; Fouache et al., 2011; Vespremeanu-Stroe et al., 2013) successfully supported the effort for high resolution paleonvironmenal investigations in prograding coastal areas and fostered the state-of-the-art of this research field. The excellent luminescence characteristics of quartz-rich marine sands and the good stratigraphy preservation potential of the BRPs make them appropriate proxies for Late Holocene paleoenvironmental reconstruction studies. During the last two decades the robust, fine-tuned chronology together with high resolution geophysical investigations of the sedimentary stratigraphy and detailed mapping of the BRP represented the methodological combination which provided eloquent data and sensible evidences to turn the understanding of simple morphogenetic models (i.e. storm waves vs. fair-weather and swell wave related BRPs, falling sea level/regressive conditions vs. rising sea level/transgressive conditions) toward more comprehensive theories reasoning on various combinations of controlling factors at work in developing BPR.

The newly produced high resolution age models of beach ridge plains from around the world (Orford et al., 2003; Armitage et al., 2006; Nilsen et al., 2006; Forsyth et al., 2012; Tamura et al., 2012; Preoteasa et al., 2013; Oliver et al., 2015; Remillard et al., 2015) deliver important information on the temporal and spatial sequencing of individual ridges, while fine-tunned evolutionary patterns and timings contribute to a better understanding of the complex interaction between sediment availability, climate variability, sea level or accommodation space in beach ridge plains formation and morphological configuration.

Variable shoreline progradation rates and associated morphological configurations of the beach ridge plains (e.g. beach ridge plain, foredune ridge plains, transgressive dunefields) have been modulated by different agents and therefore they were discussed against various factors such as: i) long term climate variability and related sea level changes (De Pratter and Howard, 1981; Goy et al., 2003; Hesp et al., 2007; Fitzgerald et al., 2007; Ribolini et al., 2011; Mauz et al., 2013; Cohen et al., 2013; Gonz et al., 2014), ii) isostasy (Orford et al., 2003; Nielsen et al., 2006; Remillard et al., 2015) or iii) local tectonics (Vespremeanu-Stroe et al., 2013), iv) sediment supply (Anthony, 1995, 2015; Brooke et al., 2008; Dillenburg and Barboza, 2009), v) changing configuration of the accommodation space (i.e. progressively greater depths with shoreline advancement) (Bristow and Pucillo, 2006), vi) major climatic events such as decadal or centennial scale recurring scale floods, storm surge and storm waves (Dougherty et al., 2004; Fitzgerald et al., 2007; Forsyth et al., 2012; De Sousa et al., 2012; Clemmensen et al., 2014).

Attempts have been made to provide global overviews of their morphogenetic characteristics (Bird, 1960; Tanner, 1995; Taylor and Stone, 1996; Scheffers et al., 2011) which resulted in well documented collections of site specific patterns of beach ridge plains formation in association with local or regional driving factors characteristics. These are reviews that summarize the formative processes, age models of beach ridges and which report main categories of palaeoenvironmental reconstruction derived from such features: sea level, catastrophic events, and climate (Tamura, 2012). Yet mostly reported formative processes of the beach ridge plains are progradation of sandy beach and berm formations in relation to fair-weather waves (coupled with aeolian foredune accumulation) (Tamura, 2012). The availability of these syntheses of BRP from all over the world, while highlighting the dominance of one or few controlling factors at local level, points to the complexity of genetic and evolutionary processes shaping these landforms when considered at a global level, as well as the difficulty to epitomize them within general, predictive evolutionary models, or to use a commonly accepted nomenclature when referring to such landforms (Stapor, 1975; Otvos, 2000; Hesp, 2006).

This study deals with the reconstruction of the beach ridge plains genesis and evolution in the Danube delta based on a new absolute chronology (Table 1), morphometrical analyses of BRP features, stratigraphical interpretation of cores and ground penetrating radar (GPR) profiles. A morphogenetic classification has been undertaken based on the spatial progradation patterns whilst the assessment of each strandplain (or subsequent ridgesets) progradation rates is discussed in relation with the resulting morphology; moreover, distinct thresholds of shoreline mobility are established for discriminating between distinct BRP configurations (i.e. low elevation ridgesets vs transgressive dunefields). Studies dedicated to large (spatial and temporal) scale coastal behavior are important as they serve as background for interpreting and understanding the present shoreline response at risk under natural and anthropogenic pressures.

Table 1
Summary of luminescence age results. Age estimations are expressed relative to 2013, the year of measurement. Uncertainties in age calculation are based on analytical errors and reflect combined systematic and experimental variability. Quoted errors represent 1σ.

Sample	Overburden (m)	Grain size (μm)	Moisture content (%)	Ge γ-spectrometry (*ex situ*)			Total dose rate (Gy/ka)	D_e (Gy)	Stat. Err. (%)	Sist. Err. (%)	Age (ka)	Coordinates	
				K (%)	Th (ppm)	U (ppm)						Lat.	Long.
Jibrieni 1	0.70	125–180	21 ± 5	0.41 ± 0.01	0.70 ± 0.1	0.28 ± 0.01	0.61 ± 0.01	0.17 ± 0.01	6.0	7.7	**0.28 ± 0.03**	45°25′43″	29°34′40″
Jibrieni 2	0.80	180–250	7 ± 2	0.19 ± 0.01	0.54 ± 0.2	0.26 ± 0.01	0.46 ± 0.02	0.36 ± 0.01	4.4	7.5	**0.79 ± 0.07**	45°25′20″	29°33′19″
Letea 1	0.8	180–250	18 ± 4	0.08 ± 0.01	1.06 ± 0.12	0.11 ± 0.04	0.35 ± 0.01	0.63 ± 0.02	4.7	9.1	**1.80 ± 0.18**	45°19′33″	29°32′18″
Letea 2	0.8	125–180	29 ± 7	0.93 ± 0.02	2.96 ± 0.17	0.92 ± 0.04	1.17 ± 0.02	1.76 ± 0.06	3.7	9.1	**1.69 ± 0.16**	45°17′1″	29°32′57″
Letea 3	0.8	125–180	31 ± 8	0.99 ± 0.02	1.73 ± 0.17	0.58 ± 0.05	1.06 ± 0.02	0.84 ± 0.06	7.3	9.4	**0.81 ± 0.10**	45°19′11″	29°33′39″
Letea 4	0.8	125–180	25 ± 6	0.89 ± 0.03	2.19 ± 0.15	0.72 ± 0.05	1.09 ± 0.02	0.37 ± 0.02	5.8	8.3	**0.34 ± 0.03**	45°17′58″	29°35′57″
Letea 5	0.80	125–180	15 ± 4	0.76 ± 0.01	3.40 ± 0.1	1.13 ± 0.07	1.24 ± 0.02	3.23 ± 0.15	4.8	6.7	**2.61 ± 0.22**	45°14′31″	29°30′45″
Letea 6	0.65	125–180	24 ± 6	0.76 ± 0.02	1.68 ± 0.2	0.64 ± 0.04	0.97 ± 0.02	2.09 ± 0.03	2.3	8.1	**2.15 ± 0.18**	45°15′49″	29°32′37″
Ceamurlia	0.8	125–180	20 ± 5	0.36 ± 0.01	1.06 ± 0.07	0.39 ± 0.03	0.71 ± 0.01	2.14 ± 0.05	2.7	8.0	**3.45 ± 0.28**	45°10′36″	29°23′12″
Cara 1	1.6	180–250	22 ± 5	0.26 ± 0.01	1.06 ± 0.05	0.34 ± 0.02	0.50 ± 0.01	2.22 ± 0.09	4.3	7.8	**4.46 ± 0.40**	45°8′43″	29°22′18″
Cara 2	0.8	125–180	18 ± 5	0.34 ± 0.01	0.74 ± 0.07	0.24 ± 0.02	0.55 ± 0.01	2.52 ± 0.06	2.7	7.5	**4.46 ± 0.4**	45°4′24″	29°22′53″
Cara 3	0.8	125–180	23 ± 6	0.29 ± 0.01	1.06 ± 0.12	0.25 ± 0.02	0.53 ± 0.01	2.07 ± 0.06	3.4	8.0	**4.05 ± 0.35**	45°4′20″	29°22′20″
Cara 4	0.70	125–180	20 ± 5	0.51 ± 0.01	0.62 ± 0.3	0.33 ± 0.07	0.69 ± 0.02	2.80 ± 0.04	3.1	7.5	**4.03 ± 0.33**	45°4′1″	29°24′2″
Cara 5	0.65	125–180	21 ± 5	0.56 ± 0.01	5.52 ± 0.2	1.56 ± 0.04	1.24 ± 0.02	4.04 ± 0.18	4.7	7.6	**3.27 ± 0.29**	45°3′25″	45°3′25″
S1	1.20	125–180	22 ± 6	0.84 ± 0.01	3.16 ± 0.07	0.97 ± 0.01	1.17 ± 0.01	1.58 ± 0.05	5.1	7.9	**1.35 ± 0.13**	44°59′41″	29°37′21″
PS_2	1.00	125–180	24 ± 4	0.82 ± 0.02	3.06 ± 0.20	0.93 ± 0.01	1.13 ± 0.02	0.32 ± 0.02	6.6	7.2	**0.30 ± 0.03**	44°55′36″	29°36′31″
Pahane	0.8	125–180	19 ± 5	0.49 ± 0.01	1.73 ± 0.10	0.64 ± 0.03	0.80 ± 0.01	2.07 ± 0.07	3.7	7.3	**2.58 ± 0.21**	44°45′17″	29°5′25″
Lupu 1	0.7	125–180	25 ± 6	0.79 ± 0.01	2.81 ± 0.07	0.81 ± 0.03	1.08 ± 0.01	4.11 ± 0.25	6.2	8.3	**3.82 ± 0.40**	44°37′10″	28°48′22″
Lupu 2	0.8	125–180	27 ± 7	0.53 ± 0.01	1.97 ± 0.07	0.50 ± 0.02	0.77 ± 0.01	2.06 ± 0.13	6.4	8.4	**2.66 ± 0.28**	44°37′31″	28°49′3″
JM[a]	0.60	125–180	24 ± 6	0.67 ± 0.01	6.06 ± 0.37	2.07 ± 0.07	1.42 ± 0.02	2.98 ± 0.09	3.5	8.2	**2.10 ± 0.19**	45°1′37″	29°37′37″

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